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Thin-film thermocouples and strain-gauge technologies for engine applications

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Abstract

Advanced thin-film sensor techniques that can provide accurate surface strain and temperature measurements are being developed at NASA Lewis Research Center. These sensors are needed to provide minimally intrusive characterization of advanced materials (such as ceramics and composites) and structures (such as components for Space Shuttle main engine, high-speed civil transport, and general aviation aircraft) in hostile, high-temperature environments, and for validation of design codes. This paper presents two advanced thin-film sensor technologies: strain gauges and thermocouples. These sensors are sputter deposited directly onto the test articles and are only a few micrometers thick; the surface of the test article is not structurally altered and there is minimal disturbance of the gas flow over the surface. The strain gauges are palladium–13% chromium based and the thermocouples are platinum–13% rhodium versus platinum. The fabrication techniques of these thin-film sensors in a class 1000 cleanroom at the NASA Lewis Research Center are described. Their demonstration on a variety of engine materials, including superalloys, ceramics, and advanced ceramic matrix composites, in several hostile, high-temperature test environments is discussed. © 1998 Elsevier Science S.A.

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1. Introduction

In order to meet the urgent needs in aeronautic and aerospace research where stress and temperature gradients are high and aerodynamic effects need to be minimized, sensors in a thin-film form are being developed at the NASA Lewis Research Center (LeRC) for surface measurement on various material systems. Sensors in a thin-film form provide a minimally intrusive means of measuring surface parameters, such as strain or temperature, in hostile environments. They are needed in engine systems to evaluate advanced materials and components and to provide experimental verification of computational models. Unlike more conventional wire or foil sensors, thin-film sensors do not necessitate any machining of the surface, thereby leaving intact the surface's structural integrity. They are sputter deposited directly onto the surface and have thickness on the order of a few micrometers (μm), which is many orders of magnitude thinner than wire. Thin-film sensors, therefore, add negligible mass to the surface and create minimal disturbance of the gas flow over the surface. Consequently, thin-film sensors have minimal impact on the thermal, strain and vibration patterns that exist in the operating environment. Two advanced thin-film sensor technologies, thermocouples and strain gauges, will be presented in this paper.

The thin-film thermocouple (TFTC) technology was originally developed for application to superalloys used in jet aircraft engines for temperature measurements up to 1000°C [1–3]. This technology was advanced through several NASA contracts and grants and extended to ceramic and intermetallic materials [4,5] used in the advanced jet engines. The work to develop and apply TFTCs at LeRC has been concentrated on platinum–13% rhodium (Pt13Rh) versus platinum (Pt) due to its high-temperature capability. They have been applied to silicon nitride, silicon carbide, aluminum oxide (alumina), mullite, ceramic matrix composites (CMCs), Space Shuttle thermal-protection-system tiles, and nickel aluminide in the temperature range 1000–1500°C [5–8]. TFTCs have undergone furnace tests as well as tests in harsh environments, including gas turbine [1] and hydrogen–oxygen engine environments under both low- and high-pressure conditions [7], a high-heat-flux facility [5,6], and a diesel engine environment [9].

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Thin-film strain gauge (TFSGs) made of NiCr have been used successfully to 600°C in gas turbine engines and component rig dynamic strain testing [10,11]. The strain gauges developed at NASA LeRC are based on a newly developed alloy, palladium–13 wt.% chromium (hereafter, PdCr). This PdCr alloy was selected by United Technologies Research Center under a NASA contract to be the best candidate material for the high-temperature strain-gauge application [12]. It is structurally stable up to elevated temperatures and its apparent strain versus temperature characteristic is linear, repeatable and not sensitive to the rates of heating and cooling. Active development based on this new gauge alloy, PdCr, is being pursued to extend its use in both dynamic and static strain testing on superalloy, ceramic and CMC components of engines and aircraft structures to 1100°C [12–15].

This paper describes efforts in the Sensors and Electronics Technology Branch of NASA LeRC in developing thin-film strain gauges and thermocouples for high-temperature applications on a range of materials. Sensor preparation techniques and procedures including thin-film sputter deposition, electron-beam evaporation, masking, and lead-wire attachment techniques are discussed. The characteristics of the sensors and their testing results on various materials and in various environments are presented.

2. Sensor fabrication

The fabrication of the thin-film sensors is completed in a cleanroom to minimize possible contamination. The class 1000 cleanroom at the LeRC contains state-of-the-art facilities including several thin-film sputter-deposition and evaporation systems, wire-bonding systems, etching systems, equipment for photolithography processes, and a surface profiler. The fabrication process of thin-film sensor systems on a particular substrate material needs to be tailored to ensure good adhesion and no chemical interaction between the sensor and the substrate material. Fig. 1 shows a schematic diagram of the thin-film sensor layer structures on both electrically insulating and electrically conducting substrates. For an electrically conductive metal substrate, such as superalloy materials (Fig. 1(a)), an MCrAlY coating 120 μm thick is first deposited onto the substrate by electron-beam evaporation or by sputter deposition. M can represent Fe, Co, Ni, or a combination of Co and Ni. With heat treatment at 1100°C, this coating forms a stable, adherent, electrically insulating alumina (Al_2O_3) layer. An additional layer of alumina is sputter deposited or electron-beam evaporated onto the surface to fill any pinholes or cracks that may be present in the grown oxide. Electrically conductive ceramic materials such as silicon carbide, Fig. 1(b), are thermally oxidized to form a stable, adherent silicon dioxide (SiO_2) layer, which is followed by another layer of alumina of the thickness needed to obtain the required insulation resistance. The thicknesses of the thermally grown oxide and sputter-deposited alumina layers are approximately 2–3 μm and 5–8 μm, respectively. The sensors are then fabricated onto the alumina layer. In the case of electrically insulating materials such as silicon nitride, aluminum oxide and mullite, Fig. 1(c), the sensors are fabricated directly onto its surface. For those applications that require a protective overcoat, a coating of alumina is deposited either by sputtering or evaporation onto the sensor to a thickness of approximately 2–3 μm.

2.1. Basecoat and overcoat

Alumina is used as both the basecoat and overcoat for thin-film sensor systems because it is stable and it has very high resistivity at very high temperatures. When deposited from a pure alumina source (99.9%), an insulating alumina thin film has an electrical resistivity as high as that of the bulk materials (5×10^7 Ω cm at 1100°C). For a 120 Ω strain gauge to be useable to 1100°C, an alumina basecoat with a thickness of 7 μm or higher is needed to provide at least 0.1 MΩ resistance-to-ground at all operating temperatures up to 1100°C.

To fabricate a dense and thick alumina layer with no pinholes or cracks, the substrate needs to be heated during sputtering or evaporation to increase mobility of the depositing atoms and to minimize thermal stress. The alumina film is therefore in extension during the deposition, and then in compression at room temperature with a level of stress high enough to compensate any expansion during use to the maximum temperature. It was found that 800–900°C is the preferred substrate temperature range for depositing an alumina layer that is useful up to 1100°C [14]. This alumina film can be put down by either sputtering or evaporation. The sputter-

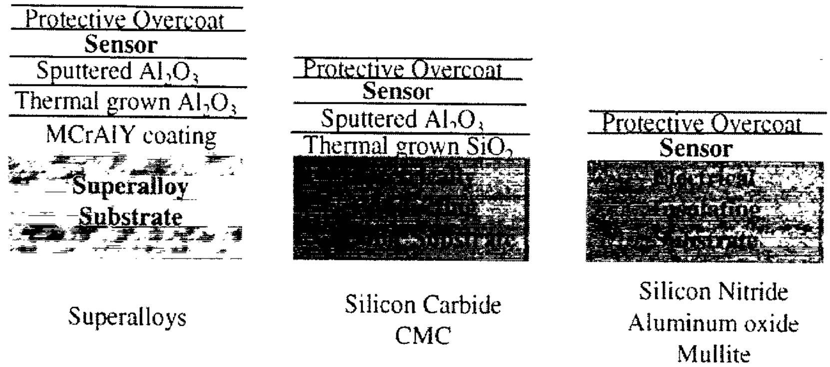

Fig. 1. Schematic diagram of thin-film sensors on various substrate materials.

Table 1
Thin-film deposition conditions for Pt13Rh/Pt thermocouple (TC) and PdCr/Pt strain gauge (SG)

Material	Target composition	Power density (W cm^{-2})	Deposition mode	Substrate temp. (°C)	Thickness (μM)
Pt (TC and SG)	Pt	1.94	magnetron	250–300	5
Pt–Rh (TC)	Pt13 wt.%Rh	1.94	magnetron	250–300	5
PdCr (SG)	Pd14 wt.%Cr	1.94	diode	25	8
Alumina	Al_2O_3	3.44	r.f.	900	6–8
Alumina	Al_2O_3	e-beam	evaporation	900	6–8

ing process is very slow, taking approximately 50 h to prepare a 6–8 μm thick alumina film compared to only 20 min needed for the electron-beam evaporation. The fabrication parameters for alumina films are listed in Table 1.

2.2. Thermocouples

The thermocouples are patterned with stenciled shadow masks during sputter deposition of the Pt and Pt13Rh thin films. An adjacent heater is maintained at 400°C during the sputter-deposition process. It is estimated the substrate is at approximately 250–300°C, as it receives radiation from the adjacent heater and is also heated by the sputtering process. The sputtering parameters for 5 μm thick Pt and Pt13Rh films are listed in Table 1.

2.3. Strain gauges

Fig. 2(a) presents a dynamic strain gauge made of a PdCr thin film. The PdCr gauge is prepared first by sputter deposition of PdCr thin film of approximately 8 μm thickness, then patterned using the photolithography technique and chemical etching with $FeCl_3$. For static strain applications, a platinum (Pt) temperature compensator element is adopted to minimize the temperature effect on the resistance change of the PdCr. This is because PdCr has a higher (but constant) temperature coefficient of resistance than that allowed for a static strain gauge. The Pt element, 5 μm thick, is located around the PdCr gauge grid and is connected to the adjacent arm of a Wheatstone-bridge circuit to minimize the temperature effect [16] (Fig. 2(b)). The Pt compensator is patterned using a metal shadow mask during deposition. The sputtering parameters for both PdCr and Pt films are listed in Table 1.

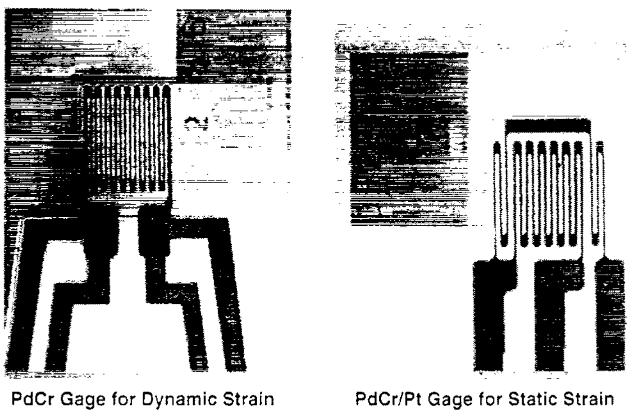

Fig. 2. PdCr-based thin-film strain gauges: (a) dynamic strain gauge; (b) static strain gauge.

2.4. Lead-wire attachment

The 75 μm diameter lead wires which connect to the measurement circuits are attached to the thin films via the parallel gap welding process [17]. Lead wires made of Pt13Rh and Pt are used for Pt13Rh and Pt TFTC elements, respectively, and Pt lead wires are used for both PdCr and Pt strain-gauge elements. The lead wires are secured onto the substrate by means of a high-temperature ceramic cement.

3. Sensor characteristics and testing

3.1. Thermocouples

TFTCs have been fabricated and tested on various substrate systems including nickel-based superalloys, silicon nitride (Si_3N_4), silicon carbide (SiC), mullite and aluminum oxide (Al_2O_3) ceramics, ceramic matrix composites (CMCs), and intermetallics. The test conditions are summarized in Table 2.

TFTCs on a nickel-based superalloy have been tested up to 1100°C in conditions similar to, though not as severe as, the Space Shuttle main engine (SSME) high-pressure fuel turbopump environment [7]. Sensors tested on flat panels at low-pressure conditions proved to be highly adherent and durable. However, when TFTCs were tested on SSME turbine blades, Fig. 3, under high-pressure high-temperature conditions, repeated stable thermal output was difficult to obtain. This may be attributed to poor contact between the thin films and lead wires. The TFTC output was unstable during changes in pressure; the vibrations of the facility during start up and shut down may also have disrupted contacts between the wire and film, thereby resulting in unstable output.

The TFTCs instrumented on ceramic materials were evaluated in ceramic tube air furnaces under steady-state and thermal cycling modes up to 1000 to 1500°C for times up to 150 h at ambient pressures [5,6]. No sensor failures occurred during this total test time. The resulting drift rate of the TFTCs varies with: (1) the absolute temperature level of the substrate material on which the TFTC is deposited; (2) the temperature gradient distribution between the thin film and the lead-wire portion of the circuit; and (3) the film thickness

Table 2
Summary of TFTC applications at NASA LeRC

Material	Geometry	Test condition	Temperature–time
Nickel-based superalloy	flat plate	hydrogen–oxygen combustion pressures to 4 MPa	0 to 900–1000°C in 5 s, 10 cycles
Nickel-based superalloy	turbine blades	SSME-type conditions; hydrogen–oxygen combustion pressures to 16 MPa	0 to 930°C in 6 s, 3 cycles
Al_2O_3 and mullite	flat plate	air furnace	1000–1500°C, 150 h static and cycling test and up to 2500°C s^{-1} thermal shock, 20 cycles
Si_3N_4 and SiC	flat plate	air furnace	1000–1500°C, 150 h static and cycling and up to 2500°C s^{-1} thermal shock, 20 cycles
HPZ/SiC CMC	hoop	burner rig with jet fuel pressure to 2 MPa	gas temp., 1500°C; surface temp., 1100°C; 25 h
SiC/SiC CMC	flat plate and cylinder	burner rig with jet fuel pressure to 2 MPa	gas temp., 1500°C; surface temp., 1100°C; 10 h

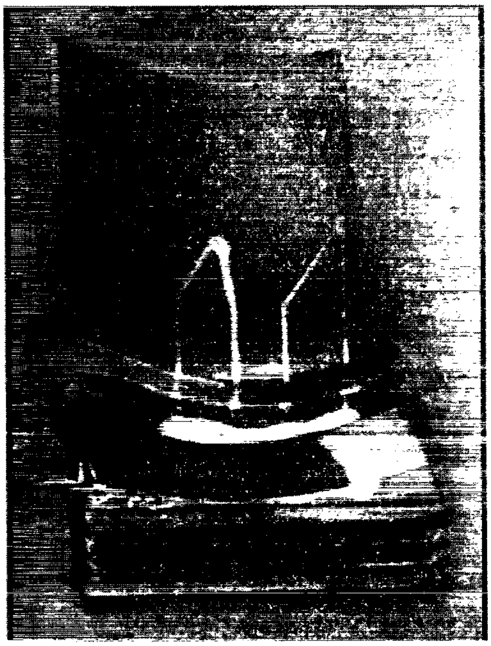

Fig. 3. Pt13Rh/Pt thin-film thermocouples applied on Space Shuttle main engine turbine blade.

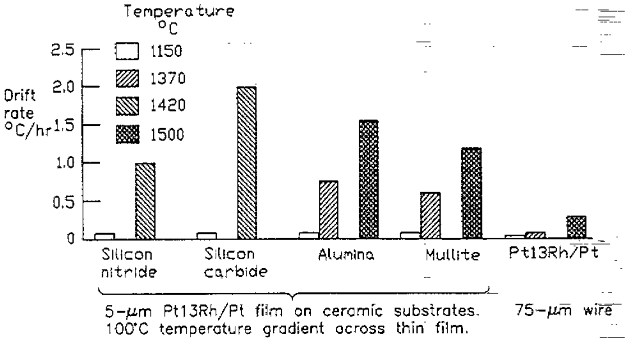

Fig. 4. Drift rates for thin-film thermocouples compared to those of wire thermocouples.

and diameter of the lead wires. At temperatures greater than about 1250°C, drift rates rapidly increase as the test temperature increases but varies for each substrate material. Selected drift rates of TFTCs on various materials and compared to that of wire TCs are shown in Fig. 4. The aluminum oxide and mullite had little visible surface deterioration after the tests, and there was very little degradation of the sensor structure. Silicon nitride and silicon carbide, however, exhibited visible surface changes at temperatures above about 1250°C. The higher purity of these silicon-based materials reduced the amount of substrate surface oxidation and interfacial reactions that can contribute to sensor failure. TFTCs on silicon nitride and mullite also exhibited good durability to survive a 20-cycle test with a heating rate up to 2500°C s^{-1} [6].

More recent applications of TFTCs have been concentrated on the evaluation of advanced CMC materials [8] designed to meet propulsion capability goals of the integrated high-performance turbine engine technology (IHPTET) and high-speed civil transport (HSCT). A hoop made of hydridopolysilazane fiber/silicon carbide (HPZ/SiC) CMC was instrumented with three TFTCs and tested in a burner rig that operates on jet fuel at pressure of 0.7 to 2 MPa (100–300 psi). The average gas-stream temperature is approximately 1500°C. A TFTC provided surface temperature data up to 1100°C for over 25 h. The eventual failure mechanism for the TFTCs was again due to the poor contacts between the thin film and the lead wires as well as the lead-wire attachment on the CMC substrate material. Several SiC/SiC CMC flat panels and cylinders are being instrumented with TFTCs and tested in the same facility. Improvements in the lead-wire attachment technique are being addressed.

3.2. *Strain gauges*

The advanced PdCr-based TFSG is a much newer technology compared to the Pt13Rh/Pt TFTCs. Their applications in harsh environments have therefore been limited. However, they have been fabricated and tested on various substrate systems including nickel-based superalloys, silicon nitride (Si_3N_4) and aluminum oxide (Al_2O_3) ceramics, and SiC/SiC ceramic matrix composites (CMCs). The test conditions are summarized in Table 3.

Depending on the application, whether for dynamic strain or static strain measurement, the requirements for a useful

Table 3
Summary of TFSG application at NASA LeRC

Material	Geometry	Test condition	Temperature–time
Nickel-based superalloy	cantilever bar and 75 μm shim	air furnace and heat-flux arc lamp	up to 1100°C and up to 1000°C s^{-1} thermal shock
Al_2O_3	cantilever bar	air furnace and heat-flux arc lamp	up to 1100°C and up to 1000°C s^{-1} thermal shock
Si_3N_4	flat plate and turbine blade	air furnace and spin rig	up to 1100°C, static and cycling under ± 2000 $\mu\epsilon$
SiC/SiC CMC	flat panel	burner rig with jet fuel pressure to 2 MPa	gas temp., 1500°C; surface temp., 1100°C

gauge may be different. For dynamic strain measurements during which the rate of change in strain is much larger compared with the rate of change in temperature even if the time period is long, the allowed apparent strain sensitivity of a gauge can be very high. The general requirements for a useful dynamic strain gauge are (1) its apparent strain sensitivity is less than 100 microstrain ($\mu\epsilon$) °C^{-1}, and (2) its drift strain rate at use temperatures is less than 500 $\mu\epsilon$ h^{-1} [10]. On the other hand, for static strain measurement over long periods of time during which both the temperature and strain may vary, the allowed apparent strain and drift strain of a useful gauge are much lower than those for a dynamic strain gauge. For a required accuracy of 10% for static strain measurements in the range of 2000 $\mu\epsilon$, the total apparent strain and the drift strain should be smaller than 200 $\mu\epsilon$, so as to be neglected, or repeatable within 200 $\mu\epsilon$, so it can be corrected.

When connected to a Wheatstone-bridge circuit in a quarter-bridge configuration, the resulting apparent strain of a PdCr dynamic strain gauge is stable and repeatable between thermal cycles to 1100°C [15]. The apparent strain sensitivity is approximately 85 $\mu\epsilon$ °C^{-1}, which is less than the required value of 100 $\mu\epsilon$ °C^{-1}. The drift strain of the gauge at 1100°C is also less than the required value of 500 $\mu\epsilon$ h^{-1}. The resulting apparent strain characteristic of a PdCr static strain gauge connected to a Wheatstone-bridge circuit in a half-bridge configuration is stable and repeatable within ± 200 $\mu\epsilon$ between thermal cycles to 1100°C with a sensitivity less than 3.5 $\mu\epsilon$ °C^{-1} in the entire temperature range. The apparent strain of this PdCr compensated thin-film gauge can be corrected to within ± 200 $\mu\epsilon$ if the uncertainty in temperature measurement is within 57°C. This PdCr-based gauge is stable and responds linearly to mechanical loads even at 1050°C. Its strain sensitivity (or gauge factor) decreases only approximately 22% from room temperature to 1050°C (1900°F) (Fig. 5).

PdCr-based TFSGs have been evaluated on various materials in an air furnace up to 1100°C and in a heat-flux calibrator with high heating rates up to 1100°C s^{-1}. Heat-flux lamp currents from 30 to 400 A are used to generate heat fluxes from about 0.1 to 2 MW m^{-2} and heating rates from about 2 to 1100°C s^{-1}. The maximum temperature was 1100°C. No sensor failures occurred after they were subjected to the maximum heat flux. These advanced PdCr dynamic gauges were also applied to an advanced turbine blade made

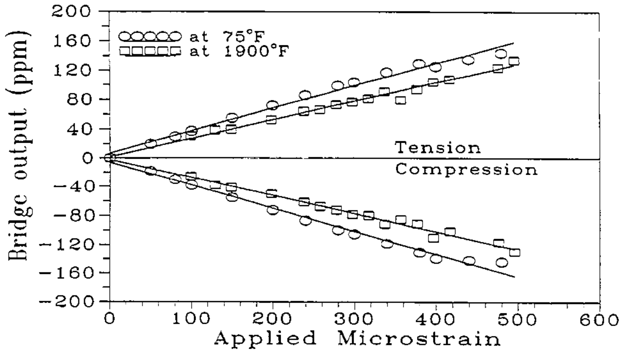

Fig. 5. Mechanical response of a PdCr strain gauge at both room temperature and 1050°C (1900°F).

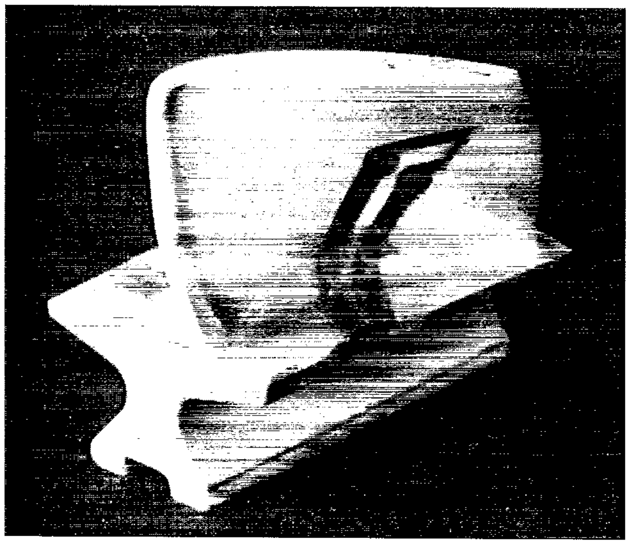

Fig. 6. PdCr thin-film dynamic strain gauge applied on a silicon nitride turbine blade. (Demonstrated by AlliedSignal Engine Co. under DOE contract No. DE-AC02-96-EE-50454 for DOE Ceramic Turbine Engine Demonstrate Project.)

of silicon nitride utilized in the IHPTET environment (Fig. 6). The gauges survive tests up to a maximum speed of 42 500 rpm and fatigue tests under ± 2000 $\mu\epsilon$, up to 1000°C for a million cycles. The gauges are now being applied to SiC/SiC CMC components for HSCT and evaluated in a burner rig that operates on jet fuel at a pressure of 0.7 to 2 MPa (100–300 psi). The average gas-stream temperature was approximately 1500°C, and the CMC surface temperature was approximately 1100°C.

A weldable PdCr-based TFSG was also developed by first fabricating the gauge on a metal shim, which was then transported and welded on the test article. It provides an option for applications where sputtering a gauge directly on a large test article is impossible or the installation of the gauges has to be done in the test field. A metal shim such as a 75 μm thick Hastelloy-X should have a similar coefficient of thermal expansion to that of the substrate material. The apparent strain curve of a weldable gauge is similar to that of the gauge deposited directly on the substrate. The mechanical response of this weldable gauge is also similar to that of a directly deposited gauge in that it is linear to the mechanical load and has no delay in transferring the strain [15].

4. Summary and future work

Measurement techniques for propulsion systems are advanced through the development of thin-film thermocouples and strain gauges. These thin-film sensors have the advantage of providing minimally intrusive measurements. Thin-film thermocouples, made of Pt13Rh/Pt, have proven to be applicable to a range of materials and applications. They have been demonstrated on superalloys, ceramics, ceramic composites, and intermetallics. Data have been obtained in furnace testing, under high-heat-flux conditions, and in harsh engine environments. Thin-film strain gauges based on a newly developed alloy, PdCr, have been developed for both dynamic and static strain applications in the temperature range from room temperature to 1100°C. This is a 500°C advance over the more conventional NiCr technology. A weldable strain gauge for applications where sputtering a gauge directly onto a large test article is impossible or the installation of the gauges has to been done in the test field has also been developed.

Future work will be concentrated on the improvements of the reliability and durability of these sensors in high-temperature high-pressure high-velocity gas-stream environments. The lead-wire attachment techniques to both the thin films and the substrate materials need to be improved. A more protective coating to protect thin-film sensors from erosion and catalytic reactions in these environments will also need to be addressed. Gauging techniques on curved surfaces is an area of further investigation. Characterization of these thin-film sensors on advanced materials such as CMCs will continue in order to establish a statistical database. In addition, the next generation of sensors that can be used to even higher temperatures (>1200°C) will be explored to address the needs for advanced aeropropulsion research.

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